Establishing a Lunar Underground Outpost

Shifting the paradigm for future space exploration, settlement and commerce

By

Dr. Greg Baiden
President
Penguin Automated Systems Inc.

Louis L. Grenier ing., M.Sc. CD [1]
Mission Manager, International Space Station Utilization
Space Exploration
Canadian Space Agency

Brad Blair
NewSpace Analytics

Dale Tietz
CEO/LTC USAF (Ret) Shackleton Energy Inc.

James S. Logan, MD
NASA Space Medical Officer (Ret)
Space Enterprise Institute

---

[1] The views expressed by the author are based on thirty-six years of professional engineering experience in both the aerospace and space sector and do not constitute necessarily an official endorsement from the Canadian Space Agency or Government of Canada on current established space policy and future directions of the space program. The content of this paper are reflections from a group of multi-disciplinary experts providing guidance material for future potential strategic directions.

Acknowledgement

At the time of republishing and updating this article, first written 20 years ago, our distinguished colleague and co-author, Mr. Brad Blair, passed away in June 2022. It is fitting that this vision of the future of settlement and mining of the moon and beyond is a part of his legacy.

Brad committed his life to space exploration encouraging all young and old to take on the challenge for humankind. Brad was a true visionary space explorer who dreamed, like us two, of a permanent human presence in space.

The NSS National Space Society paid a well thought of tribute to him.

https://space.nss.org/national-space-society-mourns-the-passing-of-brad-blair/

May your vision of space exploration and the means to get there continue unabated, Brad. We dedicate Chapter 12 to the memory of Brad Blair.

Greg and Louis

Abstract

The first generation of space entrepreneurs and their acolytes have grown weary of standard '*flags and footprints*' space exploration missions/programs historically sponsored by nation states. They are pondering more profound questions: What are the potential value propositions of space-based activities? How can *known* off-planet resources be leveraged to create vast new wealth, permanently expand the global economy into cis-lunar space, solve current real-world problems and facilitate humanity's transition from a constrained terrestrial civilization to a theoretically unlimited celestial one.

The range of promising economically feasible *commercial* space applications range from the mundane (tourism - space hotels) to the transformational (carbon-free energy beamed to earth by space solar power satellites). The ultimate success of such applications depends on four critical assets, which must all be *space-based* rather than resupplied from Earth: (1) Propellant; (2) Energy; (3) Mineral and Chemicals and (4) Space Industrial Manufacturing Capabilities (SIMC).

The cold hard physics of the Rocket Equation and the Laws of Economics mandate these assets come from non-terrestrial sources. Other than energy from the sun, the only non-terrestrial resource repository in the *local planetary neighborhood* is the moon.

Fortunately, the moon is relatively rich in the resources required to build a cis-lunar industrial base. Unfortunately, the moon is an extremely unforgiving environment. Its resources may or may not exist in significantly concentrated deposits as on earth. Huge technological and operational hurdles exist to the application of proven terrestrial approaches to finding, extracting, separating, purificating and manufacturing.

The collection of raw materials and their conversion into usable materials for expansion of the human realm is the purview of exploration, prospecting, mining and processing known as the *mining process*. This paper describes the creation and evolution of a Concept of Operations (CONOPS) consistent with known *severe* lunar constraints leading to permanent industrial presence (PIP) on the moon, how such facilities might be constructed and relevant terrestrial technologies that could enable the first of many operational mines on the moon.

BACKGROUND

The approach to date as demonstrated by the Apollo missions to the moon has been that of all self-contained sortie ‘out and back’ missions. Although unmanned robotic precursor missions were flown to better map lunar topography (Ranger) and to characterize the lunar surface environment (Surveyor), no pre-arrival infrastructure was required and lunar resources were not utilized to protect crew, extend mission capabilities or upgrade landing sites for future visits. The dual justifications for the Apollo program were national prestige and science. The former was paramount and the latter a distant afterthought.

The idea of establishing a permanent facility on the moon is not new. As early as 1959 the US army considered a permanent underground base on the moon. But even then, neither science nor resource extraction was the priority. The real reason was *Mutual Assured Destruction* by weaponizing the moon.

This paper discusses a new approach to establishment of planetary bases for the good of humankind using the upcoming Lunar return as an example. This approach is going to be a method for the establishment of initial settlements to provide the ability to survive each new planets environment.

NONTERRESTRIAL MATERIALS ARE PARAMOUNT

History may not repeat but it does recycle, If 17th and 18th century European colonists to the New World had been forced to transport every single nail, board, brick and shingle they intended to use *plus* every morsel of food they ate and every molecule of air they breathed, it is unlikely Colonial societies would have ever become a reality. Instead, colonists transported themselves, their tools and their knowledge, then utilized *local* resources found in the new world to build a new nations.

Fast forward to the 21st century and the same general principles apply although this time *tools* will likely be sent first – to make even more tools from local resources and prepare candidate areas for survival, industrial activity and eventual human habitation. These tools, however, will be in direct communication with each other. They will work in packs and swarms to accomplish specific tasks and generate construction feedstock material, supervised remotely by humans via telepresence.

Why can’t everything needed be transported from Earth by a fleet of giant rockets? The short answer is because the cold hard physics of the Rocket Equation doesn’t permit it. No matter how gargantuan the rocket – even if it is *reusable* – the fraction of rocket mass that can be dedicated to actual payload is depressingly small. The vast majority of mass in *any* rocket launched from earth using current rocket technology is *propellant*. It should be obvious that rocketing up enough Earth materals to establish permanent industrial presence on the moon, much less eventual lunar human habitation facilities, is essentially a nonstarter.

Therefore, materials used to create, construct and support industrial as well as human presence on the moon must come from the moon itself. Since it takes 33 times *less* energy to transport *anything* from the surface of the moon to low earth orbit (LEO) rather than from Earth to LEO (the moon has a much smaller gravity well than Earth), the ability to manufacture and transport propellant, the most critical component of the lunar industrial vision, from the moon to LEO is the initial keystone to support an entire cis-lunar economy.

WATER IS THE KEY

The most advanced operational rocket engines, today, utilize chemical propellants. Liquid hydrogen (LH2) and liquid oxygen (LOX) are the propellants for the most efficient rocket engines ever made. Oxygen is the most abundant substance in lunar rock. Hydrogen, unfortunately, is not present in appreciable concentrations except in lunar ice – which could, and most likely does, exist in cold traps at the bottom of permanently shadowed craters especially at higher latitudes.

ENERGY IS THE CATALYST

Harvesting water ice in shadowed craters that never exceeds minus 280 degrees Fahrenheit (95 deg Kelvin), warming to liquid phase, splitting it into constituent elements of hydrogen and oxygen, then chilling the separated components into liquid propellant will take extensive amounts of continuous, robust and reliable energy in the form of heat and/or electricity. Local solar power is not an option in permanently shadowed regions and surface solar is inefficient given 14-day long lunar nights. Small, automated, high-energy density ‘walk-away-safe’ nuclear fission power plants are likely the most promising option in the shorter term for providing 24/7 power in such environments.

HUMANS ARE NEOPHYTES IN DEEP SPACE

2022 is year 61 of human spaceflight. About 580 men and women in over 285 space missions have a cumulative experience of more than 150 person-years of spaceflight. Unfortunately, less than 0.8% of that experience is in deep space – beyond Earth orbit and the protective effects of the magnetosphere.

DRACONIAN LUNAR ENVIRONMENTAL CONSTRAINTS

A co-author (Logan) spent twenty-two years as a NASA space medical officer (flight surgeon). His job was to take care of the astronauts - and their families - during all phases of their careers – especially during missions and mission training. This experience has significantly informed our initial work.

Logan's First Law is: Space is always trying to kill you. It may kill you quickly or kill you slowly but it never *EVER* stops trying. The moon is one of the most unforgiving and harshest environments in the solar system – for men *and* machines. The only reasonable approach is to always deal with the moon as it is, not how you want it to be. You cannot conquer, cajole, overcome or negotiate with her. You must know *her* ways, respect *her* hazards and adapt to *her* reality because she does not, cannot and will not acknowledge yours. Your only weapon is a thorough knowledge of *her* many threats so an innovative Concept of Operations (CONOPS) can be evolved to evade the many ways the moon can bite you.

Lunar operational hazards come in two major classes: Physical and Biological. Examples of physical hazards are thermal stress and micrometeorites. Biological threats include ionizing radiation (from solar and galactic origins) and toxic substances. Some, like radiation and lunar regolith, are *both* potent physical and biological hazards simultaneously.

PHYSICAL AND BIOLOGICAL HAZARDS

The moon has no atmosphere or any appreciable magnetic field. As such it is totally exposed to the ravages of the deep space environment. Its 28-day orbit is locked meaning the same side always faces Earth. Both the lunar day and lunar night last 14 earth days. Surface temperatures near the equator vary widely from a boiling 250 degrees Fahrenheit (120° C, 400 K) during the lunar day and a bone chilling -208 degrees Fahrenheit (-130° C, 140 K) during the lunar night. The Moon's poles, where water/ice is located, are even colder.

The moon is a hard vacuum. The spacesuit is like a mini spacecraft. Any tear or leaky seal in the spacesuit could result in sudden incapacitation. Failure of the cooling system could result in hyperthermia. A loss of suit power or breathing consumables could also result in rapid demise. Like dangerous scuba operations, EVAs are always performed in pairs. But even then, astronauts would be unwise to stray too far from safety.

Lunar Regolith:

Because there is no atmosphere, the moon is constantly pummeled by meteors and micrometeoroids traveling an average of 17 kilometers per second (peak of 70 km/s) which, over geologic time, creates lunar soil - known as regolith - by a process lunar geologists refer to as 'gardening.'

Lunar fines are a potent physical and biological hazard. Due to their very small size – as small as 1 micron – they can penetrate seals and joints of spacesuits and spacecraft. Lunar regolith hasn't been exposed to water in several billion years so there is no mechanical weathering – as on earth – to smooth out or dull surfaces.

There are a number of terrestrial dust analog disease states that are due, in large part, to a combination of very small particle sizes and intense biological reactions. Examples include Asbestosis, Silicosis, Grinder's Disease, Volcanic Ash, 9/11 Syndrome and perhaps even Agent Orange.

Plus, if that weren't enough, these small dust particles all contain nanophase iron – extremely small particles of elemental iron with a valence of zero – not +2 or +3 forms we are used to seeing on a highly oxidized earth. In the aqueous environment of the lung these nanoparticles will most likely be absorbed directly into the bloodstream and may, if man-made nanoparticles are any guide, be able to migrate directly into the brain via tiny passages surrounding olfactory neurons in the nose – and therefore bypass the blood/brain barrier completely.

Space Radiation:

Instead of a benign nothingness, deep space is a seething undulating cauldron of dangerous ionizing radiation with enough energy to destroy molecular bonds and strip electrons off atoms creating free ions.

In space, the two *major* sources of ionizing radiation are galactic cosmic rays (GCR) and the solar wind. We know now they aren't rays at all but particles - ions actually - mostly protons with some heavy nuclei mixed in.

These elementary particles penetrate spacecraft, pressure vessels and space suits as well as organs and cells – ripping apart DNA of human occupants and other molecules (generating shrapnel-like secondary radiation called *Spallation*).

In biological systems these ions and secondary radiation induce degenerative changes usually associated with aging such as chronic inflammation, oxidative stress, cataract formation, damage to the extracellular matrix and cumulative deterioration of the central nervous system. Damage to DNA results in increasing mutation rates, instability of the genome, induction of cancers and activation of latent tumors as well as viral infections.

We know the sun, too, can unleash horrendous bursts of protons and heavy nuclei at nearly the speed of light without much warning. These Coronal Mass Ejections (CME) or Solar Particle Events (SPE) can deliver in excess of a couple hundred rem over an hour or so – a potentially lethal dose for an astronaut. So even on short-duration sortie missions you can get 'fried' by a massive solar particle event if your unlucky enough to be at the wrong place at the wrong time.

As an example, radiation was not an operational concern during the Apollo flights to the moon because mission durations were short and because of one other very important factor – LUCK! This following figure plots the radiation dose estimates for solar particle events from May 1968 to December 1969. Arrows on the x axis denote the dates of the first five manned missions to the moon (Apollo 7 was an earth orbit test mission of the Command Module) including the first two landing missions on the far right.

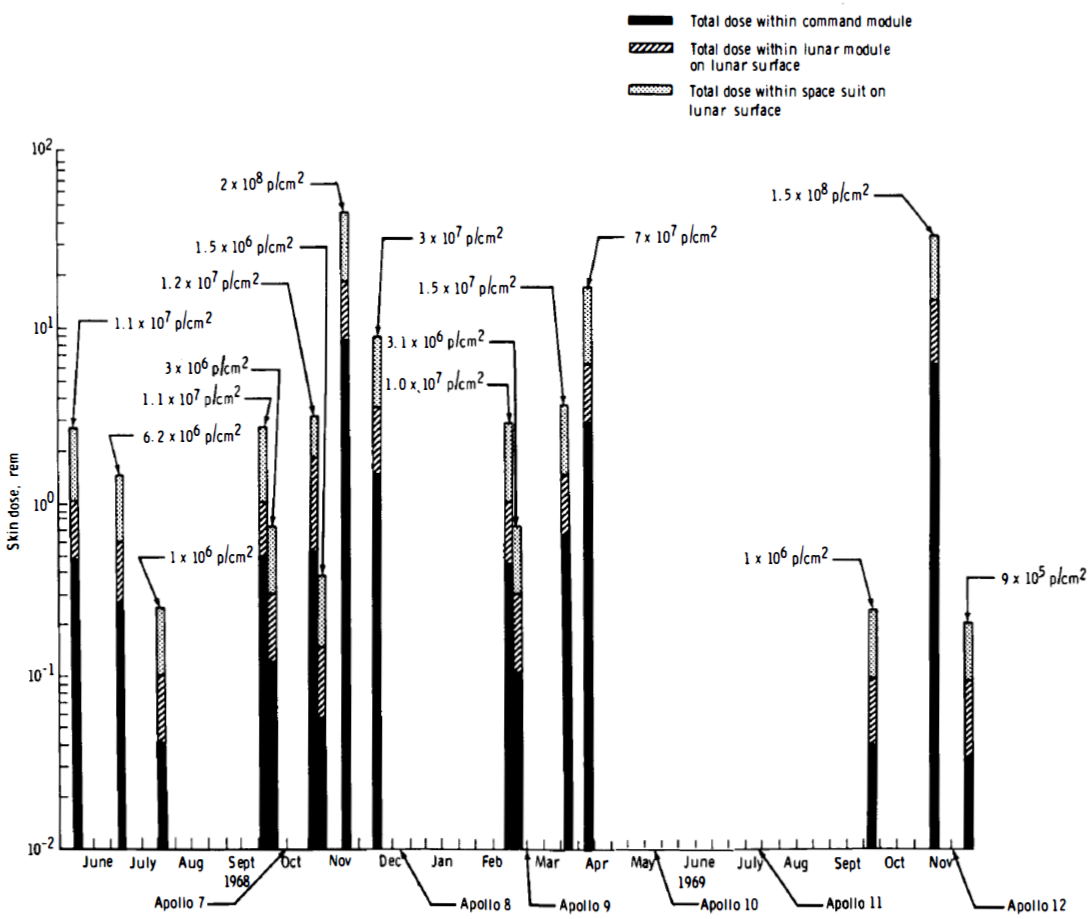


Figure 1 - Radiation-dose estimates for particle events between June 1968 and December 1969 during deep space Apollo missions to the moon.

The particular SPEs depicted above were below the threshold required to induce Acute Radiation Sickness, but several would have resulted in dose more than twice the annual limit for radiation workers on Earth all within a few days. But one in late summer 1972 gargantuan X-Class solar flare occurred – one of the few real "Granddaddy Flare" events in history. Had the Apollo 17 crew been on the way to the moon in August of 1972 rather than December, or worse, if astronauts had been *in* the lunar lander (equivalent shielding of only 5 g/cm^2) - they would have received enough radiation to cause nausea, vomiting, cataracts, internal bleeding, fatigue, bacterial infection, fever and perhaps even death due to sepsis.

Extreme solar flares are the tsunamis of space. These large ‘tidal waves’ aren’t all that rare. There isn’t much warning and they can be incredibly destructive - even lethal. And they occur on top of baseline GCR exposures.

RADIATION PROTECTION

On earth, it’s actually the mass shielding effect of the atmosphere that protects people, plants and animals from galactic cosmic radiation. To a much lesser degree the earth’s magnetosphere provides some protection, at least at lower latitudes, but it is the atmosphere that does the heavy lifting. Over every square centimeter of earth at sea-level, there is a column of air consisting of 1032 grams of mass extending from the surface to space. Therefore, our atmosphere provides a *natural*, *passive* and *constant* radiation shielding equivalent of 1032 g/cm^2 (the standard unit of radiation protection equivalent).

Astronaut career radiation limits can be envisioned as a clock that either spins rapidly (in high radiation environments) or slowly (on earth) toward a predefined limit depending on age and gender. A goal of human operations is to take measures to slow the radiation clock as much as possible – all the way down to earth speed if possible. Given today’s technology, the only way to adequately protect crew on the moon is enough mass shielding on the moon. Therefore, all human habitats and working environments will need to be buried in at least 4.12 meters of regolith preferably in solid rock. If human beings ever live or work on the moon, they’ll have to live like ants, earthworms or moles. **Habitats will need to be subterranean – one way or another. Although some traditional EVA in very limited circumstances may always exist, routine surface operations by crews in spacesuits is clearly not a viable option.** Although this may be heresy for space advocates steeped in science fiction depictions of lunar surface activities, the reality is the space radiation environment effectively precludes it.

After years of being denied, deflected or summarily ignored the ‘Elephant in the Room’ has finally staggered onto center stage for good. **Radiation is now the chief potential showstopper for extended duration human missions beyond earth orbit**. We are now faced with a radiation *Perfect Storm*: The radiation environment in deep space is significantly worse than previously estimated while at the same time empirical evidence mandates permissible radiation exposure limits be revised ever downward.

IMPLICATIONS FOR AN OPTIMIZED CONOPS

The implications of the discussed constraints force the CONOPS now described. The CONOPS will need to be ***forward deployed humans-in-the-loop using supervised remote surface & subsurface operations. These must be from radiation-protected habitats using low-latency time (LLT) telerobotics combined with autonomous operations. This style of operation will be***

required for all future space exploration whether the moon, Mars or beyond.

With the background provided regarding space hazards, this paper will discuss the need for an underground permanent outpost, how it might be constructed and the terrestrial technologies that can enable this outpost to be made and used to mine and generate the necessary resources to support human life on the moon and another planets.

Establishing a permanent underground lunar outpost and mine

Current space activity is gaining momentum with the excitement of multiple companies privately launching citizens into space. While this is exciting for the short-term brief glimpse of the earth from space will grow the enthusiasm for what else can space deliver. How will the big ideas dreamed about come to fruition? Ideas like Space Tourism in orbiting hotels, Space Orbiting Solar Power, interplanetary travel and many more to name a few. There is one very prominent challenge that must be dealt with to truly tame space! It has the most significant impact for all materials to be liberated to space it is the issues relating to the Rocket Equation. It will necessitate the substitution of *off-world* materials for those formally *rocketed up* through the Earth's massive gravity well - at *tremendous* expense as well as risk. **It will reverse the historical view of resource movement *<u>from</u>* earth-to-space *<u>to</u>* space-to-earth. If this fundamental shift in resource utilization can be made it will suddenly make economically feasible projects which formerly could never achieve cost effective closure.**

The first lunar natural resource application will be energy. Water was discovered at Shackleton Crater with the L-CROSS mission. Water is a very valuable resource in space given it can be processed to hydrogen and oxygen (rocket fuel) as discussed early in this paper. Therefore, water will be the space community's first interest in using the moon's resources as it can be provided to Low-Earth-Orbit (LEO) at much less expense then bringing it from earth. While the discovery of water was established in a gross sense, detailed exploration will be required. This should be the next focus of lunar resource utilization. Baiden and Shackleton Energy have proposed comprehensive exploration programs for the discovery of water and the production of water with refueling stations in LEO to support the exploration of the solar system and beyond. The idea of rocket fuel made on the moon is a truly a game-changing idea for space exploration. A water mining and processing venture such as this has many contemplating how to live and work on the moon supporting robotic mining operations.

Future lunar inhabitants will need to concentrate on three major activities: survival, exploration and mining including processing. As this becomes reality the focus, while currently discovery based, will change to commercial work with mining being a key anchor. Durations of stays will change from sortie type short term excursions to semi-permanent to permanent with long term manning of the mining and processing operations underground. Moreover, lunar exploration below the lunar soil in lunar bedrock has the potential to yield a similar mineral and chemicals suite to earth thus providing the resources necessary for the building of the larger projects dreamed about today in a cost effective way.

Living and working on the lunar surface will be required in this type of operation. Safety of personnel will be of prime consideration. Hazards need to be identified and designed out where possible. A preliminary list of the main necessitates are:

- Immediate
    - Generation of Oxygen
    - Generation of Water
    - Establishment of Shelter
- Protections
    - Radiation
    - Solar Flare
    - Temperature
    - Micro-meteorites

The design of any lunar base will need to address these issues so lunar inhabitants are able to survive and be protected from the environment. These environmental considerations will drive many decisions. The type of base, construction techniques, equipment and physical layout will all need to be considered closely.

All survivalists know that the most important element of survival is shelter once basic needs are met. In a lunar context this is even more important. The blocking of radiation and solar flare activity and protection from the other extremes need to be adequately designed. As all these factors are considered an underground base with sufficient depth appears to be one of the only feasible solutions. The key questions for this type of base are:

- How would this be built?
- What technology will be needed?
- Has this type of facility been built before?
- What would be the timing of such a base?

These questions are all addressed in this paper.

State-of-the-art in Robotic Mining and Construction

Robotics for terrestrial mining and construction has been the topic of a large portion of public and private mining research over the last five decades and today remains a hot topic for major changes in the way mining is done.

Inco Limited’s Mines Research group first demonstrated that long distance teleoperation of multiple mining vehicles for productive work was possible in 1994 at the Canadian Institute of Mining and Metallurgy Annual General Meeting. This demonstration had a teleoperator running two LHDs (digging machines) between the stage of the John Basset Theater at the Toronto Convention Centre and Copper Cliff North Mine in Copper Cliff, Ontario a distance of over 400 kilometers and 4000 feet underground. The demonstration was done without noticeable latency. What made this possible was an advanced telecommunications network that provided 600 Mb/s of wireless bandwidth developed by Dr. Baiden and his research team. The success of this demonstration proved that the systems developed were able to improve safety, increase productivity and lower costs. This demonstration led to the approval of a far-reaching program called the "Mining Automation Program" or MAP to development the techniques behind robotic mining.

MAP was a joint program involving Inco Limited, Tamrock OY, Dyno Nobel Explosives and Natural Resources Canada. The objective of this program was to build on the research originally developed by Inco – Mines Research. This program would develop the Operation Center concepts for the teleoperation of mobile mining machines and develop the economic case for this transformational rework of mining operations. The high bandwidth telecommunication (5G equivalent) system that could support fleet operation of mining equipment. And,a second development was the ability to provide GPS denied positioning systems for underground mining. MAP using these developments targeted building tele-robots for exploration drilling, tunnel drilling, explosives loading and ignition, material removal and transport, rock stabilization, longhole drilling and ore transportation systems.

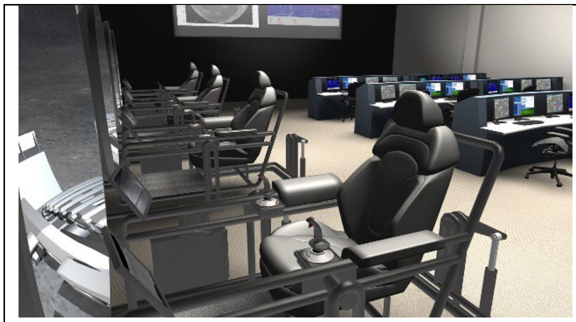
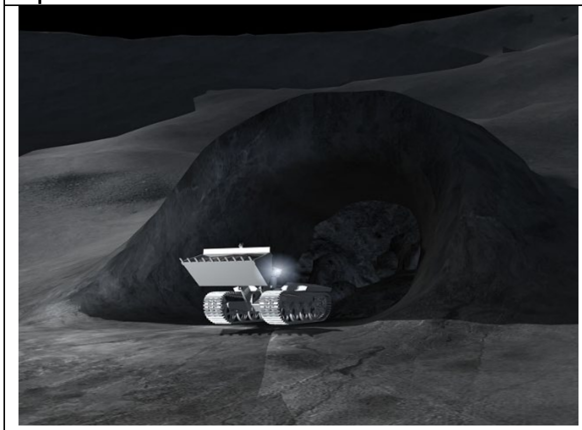
MAP had many outcomes two examples are discussed here. The first had a teleoperator running three LHDs from the safety of a centralized control centre in an industrial teleoperation workstation using remote operation combined with autonomous guidance. The second a teleoperator ran three longhole production drills from a centralized control room remotely collaring the holes and automated continuous rod addition. The machines operating in these scenarios for several years regularly from distances of 25 kilometers away with unnoticeable latency to the operator. This was all enabled by the innovative broadband telecommunication infrastructure developed by Mines Research

The outcomes of this research work is currently being applied around the world at mines in Canada, USA, Chile, Brazil, South Africa, Australia and Sweden. The accomplishment's of this research is of prime importance to the undertaking of future lunar operations as the hostile environment will necessitate the use of these techniques for outpost construction and the mining of water and other minerals/chemicals on the moon.

Development of an Underground Lunar Outpost and Mine

Establishment of an international underground lunar outpost and mining facility for supplying propellant using next-generation mining robotics can lead to a permanent Lunar outpost as a stepping-stone to further solar system exploration and settlement. This type of early lunar outpost could easily expand to support multiple large science projects as well as commercial operations. In addition, the work has many terrestrial spin-offs such as underwater mining and construction.

The underground habitat layout and possible construction sequence are shown in the figures below. These few images are a part of a large study by the authors performed for the Canadian Space Agency. In this series of images, the underground outpost starts with collaring a portal into the side of a crater to establish a garage, sleeping quarters and research facility. The excavation of all these initial requirements will be done from the earth-based operation centre as demonstrated by the terrestrial mining industry previously. Once these are complete, the first major component to install would be a collar **water-lock**. At this point the outpost can begin to be habited by astronaut/settlers. Initial lunar base pre-development work will require an Earth-based control centre for teleoperation of construction and mining robotic equipment. Several teleoperation workstations optimized for managing the latency between earth control and lunar operation would run from a control room on Earth.

	
Earth control centre for lunar operations.	Operations consoles showing view of LHD.
	
Excavation of portal entry	Installation of primary airlock

Polymer spray lining of tunnel

Certification of initial facility

Figure 2. Construction sequence for early shelter habitat.

Preliminary analysis indicates that these systems offer a feasible solution to building and certifying a radiation safe underground lunar facility. Unit energy (kW per cubic meter) for lunar excavation is expected to compare to that used in analogous terrestrial mining, tunnelling and drilling operations, enabling time, volume and equipment productivity estimates to be derived from mining practice and modified as needed to suit the lower gravity, etc. It is assumed that a majority of operations will be conducted in a sealed and partially pressurized environment, reducing the wear and abrasion of equipment and enabling the use of standardized dust management practices. Ground support would be performed using a sintering process. Estimates of the amount of microwave energy required to sinter lunar regolith [see Wingo, 2007] enable calculation of the power required for structural tunnel support and sealing.

As habitation is beginning the construction machinery can continue to advance facilities deeper underground. This can be followed by the building of science experiments such as astro-particle observatory and/or infra-red telescope. Construction scenarios shown above can be used to generate a detailed view of the “concept of operations” typically associated with space mission planning. These operational scenarios should be based on terrestrial mining industry experience for the underground construction of development and production drifts, ramps and block “cave” mining operations.

Underground Lunar Mining and Processing

Achievement of a commercial mine would follow outpost establishment. Mining and processing, using a preferred mining method such as “Block Caving” would be able to produce rock with entrained water. In an attached underground propellant processing facility the manufacture of ore (water entrained rock) would be sent to processing elements such as heating and hydrolysis to produce hydrogen and oxygen. The products would be liquified and stored in underground tanks for loading and transport to LEO

Economic Leverage of Lunar Resources

Learning to live off the land will add vitality to human space settlement, and will create new jobs, industries, markets and natural habitats as humankind expands its economic sphere. From the potential of Helium 3 (3He) as fuel for future fusion energy, to the production of Hydrogen, Nitrogen, Carbon and Oxygen to support space exploration mission logistics, to future surface manufacturing of system components from Aluminum, Titanium, Iron, Silicon, ceramics and glass, lunar resources pose a significant opportunity for the future.

> *"The space frontier will inevitably increase the scale of thinking and risk taking by business. When we are dealing with space, we are dealing with a technology that requires a planetary scale to stage it, decades of time to develop it, and much bigger investments to get across the threshold of economic return than is customary in business today. Business must now think in international terms and in terms of the next business generation. It must step up to the big risks with the same vision that enabled an earlier generation of builders to push railroad tracks out across the wilderness and lay the foundations of our modern economy."* Ralph Cordiner [from Webb, 1964]

Indeed, the visual of an expanding three-part sphere of influence composed of exploration, economic development and mature economic operation, can be used to describe highly successful prior empires from the Phoenicians, to the Romans, to England and finally the USA.

The first anticipated commercial use of lunar resources is the supply of rocket propellant to government and future private users of the Moon and lunar facilities. The simple addition of an ISRU refueling station to an early lunar surface outpost would dramatically reduce the size requirements for a steady-state cislunar transportation system [Blair, 2002] by removing the need for the heavier expendable first stage of a two-stage lunar lander. This approach would add robustness and sustainability to current NASA planning. Current expendable vehicle technology could be modified for re-use, collapsing the steady-state hardware requirements for any time lunar access to a reusable lunar lander and upper stage [Blair, 2002 and Diaz, 2005]. Only the crew capsule would be expended upon re-entry into Earth orbit. Surface mobility benefits for refuellable rover power systems are equally significant. A source of consumable fuel cell reactants on the lunar surface would enable energy-intensive applications such as mining, construction or robust and power-rich human exploration operations using a closed rover. The possible existence of Platinum group metal enrichment among the diverse geologic surface environments of the Moon offers rationale for diversified commercial lunar mining [Wingo, 2004]. Unique features such as the dense nearside mascon’s that underlie the Lunar Mare offer fodder to the imagination regarding the longer-term potential for underground mining.

Mining the moon is a precursor activity to a much more robust set of long-term mature industrial operations that will take maximum advantage of the unique lunar environment. The list of valuable research activities enabled by the thermal and vacuum conditions on the lunar surface (including permanently shadowed areas) includes materials and metallurgy research, thin film technology (large-scale), vacuum welding, coating, distillation and superconductivity research to name a few [Ruzic, 1965]. Access to cold traps and the potential for large-scale (tens to hundreds of meters) passive cryogenic systems could enable a new era in low-temperature science and engineering. Active cooling to micro or milli-Kelvin from one of these cryostats would require orders of magnitude less energy than used today for cryogenic research [Ruzic, 1965].

Summary

Lunar mining or ISRU as it has been called in the space world is now required to become a reality. The recent find of significant water on the moon means that the moon as a fuel source will change many of the plans in a positive way.

The paper has explored the creation of a lunar outpost, how mining might occur, how terrestrial techniques will likely become the basis for future mining equipment and systems on the moon, and why these facilities are important for astronaut/settler long term health and safety.

The creation of outposts on the moon and mining and processing appears to be feasible given techniques that have already been explored. Moreover, the concepts will be required to continue the human journey of exploring the solar system and beyond.

Next Steps – Future Research Initiatives

Making this CONOPS a reality is going to require several steps. The first most pressing will be the creation of a Lunar De-risking Facility to conceive, experiment and build the terrestrial precursor to the subterranean lunar outpost. This work must coincide with progress in establishing the needs of a lunar settlement such as energy and other uses.

Lunar De-risking Facility

Prior to building such an outpost on the moon it makes sense to create a terrestrial Lunar De-risking Facility. This has been proposed as the International Institute for Space Mining [Baiden and Tietz, 2010]. The concept is to create a terrestrial testbed the simulate the conditions of space and the moon in a large 250 metre cubed underground tank facility. This facility would be flooded to provide large scale conditions of weightlessness, space vacuum and thermal characteristics on earth to simulate robotic construction on the moon from earth.

A concept of the facility has been developed by Baiden . Within the facility would be an underwater/underground construction simulator for tele-construction of a lunar underground base. This physical simulator would support real conditions for robotic construction of the base in weightless conditions. Additional chambers would allow the largest thermal vacuum chamber in the world due to being constructed in a large rock cavern.

Establishment of a Lunar Outpost

The establishment of radiation-protected subterranean lunar habitats for extensive lunar resource extraction and processing will turbocharge space exploration and settlement. It will also seed an exponential expansion of cis-lunar commerce paving the way for breakthroughs in human survival and growth in the solar system and beyond. While initial uses of the moon will likely emphasize energy and spacecraft propellant production (and storage), critical materials derived from lunar feedstock will play an ever increasing role in celestial as well as terrestrial civilization.

Energy is the key to human survival on *and* off Earth. Technologies emanating from the challenges of lunar settlement will radically enhance energy management and multiply potential energy strategies on earth. Technical breakthroughs required for successful off-earth settlement will undoubtedly *spinoff* innovative applications for other energy modalities as well: fusion, fission, geothermal, wind, tidal, biofuels and magnetics to name a few.

Potentially the most significant impact of non terrestrial materials manufacturing capabilities will be the liberation of humankind from the cold hard physics of the Rocket Equation. Substitution of *off-world* materials for those formally *rocketed up* through the Earth's massive gravity well - at *tremendous* expense as well as risk - will reverse the historical arrow of resource movement *from* earth-to-space *to* space-to-earth. This fundamental shift in resource utilization will suddenly make economically feasible projects which formerly could never achieve cost effective closure.

Non terrestrial materials manufacturing could usher in the long anticipated Age of Space Solar Power in which carbon free energy could be generated by solar power satellites, built in space with space-based materials, and beamed almost anywhere on earth 24/7. This technology would be nothing less than transformative for an increasingly troubled planet.

There is **no energy shortage** in the solar system, only an innovation and creativity shortage in the realm of human endeavors.

Afterward

Perspectives from a member of the Canadian Space Program

Having served 20 years in the Canadian Space Program, I propose to share new insights for students, scholars, or young entrepreneurs interested with space exploration within the framework of lunar mining and energy. These insights may guide future research keeping in mind potential large breakthrough for the betterment of humanity.

Early on, I was mandated with the drafting of the Space exploration strategy. The Canadian Space Agency approved it in 2006, and 16 years later the key objectives are still relevant today. Next, I took on the Space Science Director-General challenge to propose what could be the next great Canadian investment comparable to the Canadarm. I submitted a service paper proposing the development of electric rovers for lunar and Martian exploration with Earth spin-offs for electric vehicles. I also took care to bring under the tent 'non-space' players such as Bombardier with a strong transport legacy in harsh environments. The service paper received wide acclaim internally and the CSA president championed it.

I proceeded with a series of socio-economic studies to compare surface mobility benefits against other technologies. Those studies demonstrated that electric mobility was the best strategic investment for Canada. President MacLean proceeded with making a proposal to the Minister of Industry to invest in rover prototyping.

The Harper government announced a $110 million supplemental funding to develop electric rover prototypes. Some of these prototypes gathered visibility with VIPs. Prime Minister Trudeau came with his daughter to visit CSA's facilities with a fateful 'pit stop' in the lunar rover sand laboratory. The rovers were also showcased in various places, including Ottawa's Parliamentary scene.

PM Trudeau visited CSA again, to announce a large investment ($2.05 Billions over 24 years) for lunar exploration with a commitment to participate in the NASA Lunar Gateway orbiter and sending rovers to the Moon.

In a nutshell: don't shy away from big dreams, articulate them well, and eventually people will pay attention.

For the second part of my CSA career, I fulfill responsibilities as mission manager, International Space Station (ISS). I lead the development of science payloads, the certification of equipment to be launched to the ISS in order to perform life science investigations on astronauts who willfully choose to volunteer in those experiments.

The experiments I had the privilege to work on are wide-ranging from loss of foot sensitivity to touch, cardiovascular physiological changes, bone loss, changes in ocular globe rigidity, psychological impact of long-term confinement, neuro-vestibular impacts to vision perception of distances and sizes of objects.

Through these studies I got a better appreciation of how the human body adapts to a change in environment but at the same time the impact on rapid ageing. The knowledge gathered through these successive 6-month missions will be very useful to help crewmembers adapt to long duration stay on the Moon and to long-distance travel to Mars. I also participate in the development of a new neutron spectrometer that will be tested on both the ISS and the Lunar Gateway. It will become an indispensable tool to warn crewmembers of exposure to high energy particles, and to, hopefully, seek shelter in underground facilities proposed in this paper.

But I would like to share an even more important perspective. I have seen rapid changes in how space business is conducted, and it is a fair assumption that future changes will occur at an even faster pace.

This is very exciting for a young person considering a career in space. When I left a comfortable aerospace career in the private sector and joined the CSA, the shuttle was the sole access-to-space vehicle. With astronomical operational costs and two very unfortunate fatal accidents, it became clear that either the human spaceflight program would be curtailed or other avenues would have to be sought after.

In the short-term, NASA negotiated agreements to ferry US crewmembers on Russian vehicles until Lorry Garver made a very bold proposal to the US Administration under the leadership of President Obama to seek commercial launch services from billionaire private entrepreneurs having made fortunes in Silicon Valley. The COTS program was born out of this brave idea.

What we are now witnessing is that Firm Fixed Price contracts foster timely, near-on-budget, and efficient innovation (i.e. the SpaceX contract to supply goods and astronauts to the ISS) while Cost Plus contract seem to lead to substantial schedule delays, and cost overruns.

For instance, the outcome of the Space Launch System (SLS) will be a pivotal moment for the US Space Program. With a bit of luck on their side, it will be proven to be a flightworthy and reliable vehicle but at a significant cost because it will not be reusable compared to SpaceX equivalent Starship vehicle. Under that scenario, how many shipsets will the US government be willing to spend to send astronauts to the Lunar Gateway? Furthermore, the SLS does not seem to have sufficient specific impulse to actually land on the Moon.

This means that SpaceX Starship will become essential if the intent is still to send astronauts on the lunar surface to establish a permanent settlement. For the worse-case scenario, the SLS will drag further into technical difficulties, and at some point, the US government will have to make a very difficult but equally strategic decision to no longer manage the development of human-rated launch vehicles and leave it to new space companies that have demonstrated their capability. The future seems to move rapidly with extremely wealthy private entrepreneurs who are gifted at attracting only the best engineers and technicians out there, who are willing to commit to become doers and problem solvers.

A similar change is happening with the type of people that are flying in space. Space used to be exclusively the privilege of highly skilled professional astronauts. However, with SpaceX, we have just witnessed the first private astronaut mission to the ISS. It looks like there will be a diversification in the field of astronaut recruitment and training.

With both launch capacity and crewmember selection, space agencies may decide to resort to pay for those services from the private sector.

One final observation along the theme of sustainability with a potential direct link with lunar mining commercial business. We have witnessed over the last 15 years a rapid acceleration of investment into clean tech on Earth to reduce the carbon footprint in the atmosphere. One promising area, which has been around for at least 45 years, is the prospect of portable, scalable nuclear fusion.

The initial concept that hasn’t proven successful so far, has been for governments to pool resources into large scale and complex nuclear fusion reactors such as ITER in France. Other ideas, that have been put aside by government research establishment have re-emerged and embraced by bright and visionary nuclear physics scientists.

One such example is the remarkable story of Dr. Michel Laberge, a gifted Canadian nuclear physics scientist who has kick-started a company, General Fusion, in British Columbia with the goal of commercializing a nuclear fusion reactor at a much smaller scale and cost than large governmental projects.

What is most interesting is the fact that while he used at the beginning to get seed funding from government, he has now attracted attention from Silicon Valley billionaires investing large sums of money on the promise of tangible results. It happens that some of these folks are very successful space entrepreneurs with a vision for transitioning from fossil fuel energy to clean, radiation-free nuclear fusion energy.

So, lunar mining could be linked with clean nuclear fusion. The Moon has been characterized with having deposits of Helium 3, the ideal gas that could be used in fusion reactors because the reaction will not release damaging high energy neutrons. What has yet to be done is to determine the sites of abundant He-3 and whether it is concentrated enough to justify economically profitable extraction. Therefore, once we get a permanent settlement on the Moon, it will become essential to survey and determine those parameters.

Of course, this assumes that Laberge or other scientists at the helm of start-ups will achieve commercial success. There is a good probability that the chance of success exists given the large sums of money invested by billionaire entrepreneurs.

It is no longer utopic to posit that if He-3 is found in profitable quantities, it could justify cargo shipping back to Earth with reusable SpaceX rockets in order to fuel the portable nuclear fusion reactors of Michel Laberge and the likes.

Commercial nuclear fusion would be a game-changer just as Edison light bulb successful breakthrough change our concept of living beyond mere daylight. The careful and wise integration of space capabilities with nuclear fusion clean tech may herald the possibility to homo sapiens to aspire moving from a fossil fuel planet to a fusion one.

Curious people ought to invest time and recognize these amazing possibilities. The integration of cleantech energy with space exploration is inevitable. The future on Earth is very bright, it is up to all of us to believe in it.

Perspectives from a member of the International Mining Industry

Miners work in any situation where mineral can be mined at a profit. The moon and beyond are no different. Miners work on earth establishing operations in the most difficult places on earth because humanity needs the mineral riches of the earth and beyond to progress. If there is a requirement miner’s will be there. While miners look for a profit in what they do, for the most part miner’s are given the privilege of mining by society and society bestows the profit as miners support humankinds progress.

This paper was developed by a mining engineer, a geologist, a government space advocate, a space entrepreneur and a medical specialist, all space enthusiast’s hopeful of a future in space for exploration, settlement and commerce.

Terrestrial mining technology is progressing slowly and rapidly at the same time. The history of mining has seen a move from hand tools, through mechanization and now through to robotics and automation using advances in information technology to improve safety and profitability, The work being done in mining industry robotics has been recognized by the Canadian Space Agency and NASA as leading work in the world. This paper briefly discusses the implications of this work for the future of both terrestrial and extraterrestrial mining.

The work developed here represents a new perspective regarding the current approach to space driven by practicality. We have learned a lot since the original writing of this paper nearly 20 years ago. Probably the most important lesson is space is always trying to kill life at every turn. This is very similar to the challenges of deep underground, arctic mining, and underwater mining. The mining industry deals with similar the kinds of operations day in and day out. That said we always mitigate that risk safely. The deepest underground mine in the world today is over 3.84 km. Mines also exist in the coldest climates on earth dealing with -65 degrees Celsius. Mine's exist at the highest altitudes. The challenges of the moon are in some cases more substantial and in other ways easier and can be overcome. I think I speak for all miners in saying the mining industry will always be there to support humankind in new endeavors

This paper represents a fresh approach to the concepts of extraterrestrial mining as each new step humankind makes will require mining to generate the materials necessary to progress.

References

Steffen, Olaf. “Explore to Exploit: A Data-Centred Approach to Space Mining Regulation.” *Space Policy* 59 (February 1, 2022): 101459. https://doi.org/10.1016/j.spacepol.2021.101459

Baiden, G.R., “Mining on Earth the Analogy-From Prospecting to Product”, LSIC Excavation and Construction Workshop, Johns Hopkins, 2021.

Hofmann, Mahulena, and Federico Bergamasco. “Space Resources Activities from the Perspective of Sustainability: Legal Aspects.” *Global Sustainability* 3 (ed 2020). https://doi.org/10.1017/sus.2019.27.

Santomartino, Rosa, Luis Zea, and Charles S. Cockell. “The Smallest Space Miners: Principles of Space Biomining.” *Extremophiles* 26, no. 1 (January 6, 2022): 7. https://doi.org/10.1007/s00792-021-01253-w.

Xu, Fengna. “The Approach to Sustainable Space Mining: Issues, Challenges, and Solutions.” *IOP Conference Series: Materials Science and Engineering* 738, no. 1 (January 1, 2020): 012014. https://doi.org/10.1088/1757-899X/738/1/012014.

Baiden, G.R., “Tele-robotics for hang-up assessment and removal – an idea whose time has come”, Society of Mining Engineering Annual Meeting, Denver, CO, 2017.

Baiden, G.R., “Geospatial mapping and surveying robotics for both GPS and GPS denied environments”, UG Mining Technology Conference, Sudbury, Canada, 2017

Baiden, G.R. and Tietz, D., “International Institute for Space Mining – A space mining de-risking facility”, FEDNOR workshop, Sudbury, Canada, 2016.

English, R.A., Benson, R.E., Bailey, J.V. and Barnes, C.M. “Apollo Experience Report – Protection from Radiation”, Technical Note TN D – 7080, March 1973.

Baiden, G., Bissiri, Y., Seguin G. and Persingher M. “Effects of Adding Vibrotactile Feedback on Operators’ Cognitive Load in Mobile Vehicle Teleoperation. The Journal of Field Robotics, Wiley, September 2007, submitted.

Baiden, G. and Bissiri, Y., August 2007, An Innovative Approach using Telerobotics for Intelligent Block Caving Operations, IFAC MMM Symposium proceedins, Quebec City, Quebec, Canada.

Baiden, G. and Bissiri, Y., A Intelligent Algorithm for a teleoperation operation: Multiple machines and multiple operators, IEEE, ICOM05 conference proceedings, category: Intelligent computation, May 2005.

Baiden, G., 2005, Telerobotic Experiments for Mining, Bulletin Can. Inst. Min. Metal,

Poole, R., Golde, P., Baiden, G. and M. Scoble, 1998. A Review of Inco's Mining Automation Research in the Sudbury Basin. Bulletin Can. Inst. Min. Metall., Montreal, 91, pp. 68-74.

Vagenas, N., Scoble, M. and G. Baiden, 1997. Mobile Machine Automation in Underground Metal Mining. Bulletin Can. Inst. Min. Metall., Montreal, 90, pp. 57-62.

Poole, R., Golde, P., Baiden, G. and M. Scoble, 1997. Multiple Machines-Single Operator on Surface at Inco's Stobie Mine. Bulletin Can. Inst. Min. Metall., Montreal, 90, pp. 63-67.

Baiden, G.R.; Strom, R.; and Preston, C., 1997. Mining automation program. Bulletin Can. Inst. Min. Metall., Montreal, 90, p.71-77.

Vagenas, N., Scoble, M. and G. Baiden, 1996. Mobile Machine Automation in Underground Metal Mining. Int. Jnl. Mineral Resources Engineering, Imperial College Press, London, 5, 1, pp. 43-55.

Baiden, G.R., 1996. Future robotic mining at INCO Limited: The next 25 years. Bulletin Can. Inst. Min. Metall., Montreal, 89, p.36-40.

Poole, R.A., Golde, P., and Baiden, G.R., Remote operation from surface of Tamrock Datasolo drills at Inco’s Stobie mine, Bulletin Can. Inst. Min. Metall.,89, pp. 47-50.

Baiden, G.R., and Henderson, E., LHD Tele-operation and Guidance - Proven Productivity Improvement Tools,Bull. Can. Inst. Min. Metall., 87, pp. 47-51.

Baiden, G., Scoble, M. and S. Flewelling, 1993. Robotic Systems Development for Mining Automation. Bull. Can. Inst. Min. Metall., 86, 972, pp. 75-77.
Baiden, G. and M. Scoble, 1992. Mine-Wide Information System Development. Bull. Can. Inst. Min. Metall., 85, 960, pp. 65-70.

[Cohen, 2002] "SELECTED PRECEPTS IN LUNAR ARCHITECTURE", M.M. Cohen, IAC-02-Q.4.3.08, 53rd International Astronautical Congress, The World Space Congress - 2002, 10-19 Oct 2002/Houston, Texas.

[Dartnell, et. al., 2007] "Martian sub-surface ionising radiation: biosignatures and geology", L. R. Dartnell, L. Desorgher, J. M. Ward, and A. J. Coates, Biogeosciences, 4, 545-558, 2007.

[Jablonski and Ogden, 2005] A.M. Jablonski, K.A. Ogden, "A Review of Technical Requirements for Lunar Structures - Present Status", International Lunar Conference 2005.

[Blair, 2002] B. Blair, J. Diaz, M. Duke, E. Lamassoure, R. Easter, M. Oderman, and M. Vaucher, “Space Resource Economic Analysis Toolkit: The Case for Commercial Lunar Ice Mining”, Final Report to the NASA Exploration Team, Center for the Commercial Applications of Combustion in Space, Colorado School of Mines, Golden, Colorado, December 20, 2002.

[Cordiner, 1961] R. Cordiner, “Competitive Private Enterprise in Space”, Chapter 10 in Peacetime Uses of Outer Space, Simon Ramo, editor, McGraw Hill Book Company, 1961, pp. 213-240.

[Diaz, 2005] J. Diaz, B. Ruiz, B. Blair, M. Harsch, M. Duke, C. Parrish, D. Lueck, R. Mueller, J. Whitlow, D. Boucher, K. Nock, P. Penzo, J. Sanders, S. Baird and K. Romig, “STARLITE - Space Transportation Architectures and Refueling for Lunar and Interplanetary Travel and Exploration,” NASA Grant NAG9-1535, Center for the Commercial Applications of Combustion in Space, Colorado School of Mines, Golden, Colorado, June 5, 2005

[Ruzic, 1965] N. Ruzic, The Case for Going to the Moon, GP Putnam’s Sons, New York, 240p.

[Baiden and Tietz 2010] G. Baiden and D. Tietz, International statute for Space Mining, confidential presentation.

[Webb, 1964] J. Webb, Administrator, National Aeronautics and Space Administration, Keynote Speech at Armed Forces Communications And Electronics Association, May 20, 1964, Washington, D.C.

[Wingo, 2004] D. Wingo, *Moonrush: Improving Life on Earth with the Moon's Resources*, Apogee Books Space Series 43, 2004, Softcover, 260pp.

[Wingo, 2007] D. Wingo, G. Woodcock, M. Maxwell, “Lunar Outpost Development and the Role of Mechanical Systems for Payload Handling, Deliverable Under NASA Contract NNL06AE27P”, Skycorp Incorporated, Huntsville, AL 35801, February 10, 2007.